INFLUENCE OF LUBRICANTS AND POLYMER COATINGS ON PENETRATION OF OCEANOGRAPHIC CORING TOOLS

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UNITED STATES
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THESIS

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The friction developed on the inner and outer faces of oceanographic coring tubes tends to decrease penetration and gross recovered length and to increase sample disturbance. An effort was made to decrease this friction through use of lubricants and polymer coatings and to thereby increase the penetration of smooth steel surfaces into fine grained sediments. Tests were conducted in the laboratory using steel plates and an Atwood test apparatus, and at sea using gravity corers. In the laboratory tests the lubricants STP, CRC, zinc grease, and lithium grease increased penetration 46, 25, 24, and 20 percent respectively. Tests at sea showed that use of STP lubricant increased corer penetration 18 and 35 percent and gross recovery length of cores 16 percent. Statistical analysis indicated that the above increases were highly significant. Teflon, FEP film, and nylon increased penetration 20 to 30 percent in the laboratory and merit special consideration since these coatings would not contaminate the core sample.

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INTRODUCTION

Methods to increase the length and the integrity of deep sea cores are constantly being sought by those working with sea floor sediments. The friction developed on the inner and outer faces of the coring tubes is one of the forces which decreases corer penetration and gross recovered length and increases sample disturbance.

Piggot (1941) first described the manner in which inner friction distorts and shortens core samples. As the sediment enters the tube it adheres to the wall of the tube and thereby builds up an increasing resistance to the entrance of additional material; the core then behaves as a solid rod. Consequently cores are not as long as the instrument penetration, and are apt to contain material from depths greater than the core length.

Hvorslev (1949) conducted a thorough study of the forces involved in the securing of long, undisturbed cores. He noted that although the friction forces (inside and outside wall friction) are dependent upon the normal forces and the coefficients of friction, they may in some cases be increased by adhesion. Inside wall friction was found to be the most important single source of sample disturbance. Tests of layered clay and adhesive soil illustrated that internal wall friction during penetration produced convexities and distortions of soil layers. Very soft, sticky soils were subject to great lateral deformation because inside friction and adhesion were quickly developed even with considerable clearance at the cutting edge.

Outside wall friction and point resistance were found to be the chief causes of decreased penetration. Rosfelder (1966) states that wall friction is the main cause of decreased penetration when coring in soft sediments, though nose resistance may be the main cause in hard beds.

The work of Hvorslev (1949) showed that the small friction of a well engineered gravity corer during its first 40 to 75 centimeters (15 to 30 inches) of penetration permitted 100 percent recovery, but that with additional length the percent recovered is proportional to the depth penetrated. The maximum "safe" or "undisturbed" length, L_s, of cohesive sediments was approximated by the equation, L_s = 10 to 20 D_s, where D_s is the minimum inner diameter of the core barrel or core liner.

Efforts to reduce friction have centered on improvements in the design of the coring tools. Piggot (1941) suggested decreasing the diameter of the cutting shoe and increasing its outside diameter beyond that of the tube. Hvorslev (1949) tested this idea and found that external wall friction in plastic sediments was reduced by the greater outside dimensions of the core nose which creates a gap between the barrel wall and the sediment. He recommended that long samplers in cohesive sediments have an inside clearance ratio, C_i, of 0.75 to 1.5 percent, $C_i = (D_s - D_e)/D_e \cdot 100$, where D_s is the minimum inside diameter of the core barrel or core liner and D_e is the minimum inside diameter of the core nose; an outside clearance ratio, C_o, of less than three percent, $C_o = (D_w - D_t)/D_t \cdot 100$, where D_w is the maximum outside diameter of the core nose and D_t is the outside diameter of the core barrel; and an area ratio, C_a, of less than 10 percent, $C_a = (D_w^2 - D_e^2)/D_e^2 \cdot 100$. A greater area ratio was considered permissible if the sampler had a stationary piston or a very small cutting edge.

Kullenberg (1947) developed the piston corer in order to overcome the effects of wall friction within the core barrel. A gravity corer has no piston, while the piston corer is so designed as to cause the piston to stop just above the sediment surface while the weighted corer continues to fall and penetrates the bottom. The suction produced compensates for wall

friction and may allow the core length to equal the penetration. Though it was generally assumed that piston samplers collected undisturbed samples with gross recovery ratios of 100 percent, several reports indicate that this is not the case (Richards, 1961). Kallstenius (1958) reported that soft strata between rigid strata may be squeezed out in piston samples without it being possible to detect the loss. There are also reports that the uppermost sediment layers may be lost or thinned by part of the material being dragged down along the inner wall of the corer as the piston moves upward (Ross and Riedel, 1967). A comparison of recovery ratios of simultaneously collected piston and gravity cores made by Ross and Riedel showed that piston cores were shortened relative to the gravity cores.

Modifications of the piston corer were reviewed by Hopkins (1964). Kermabon et al. (1966) designed a split piston to prevent a suction effect on the core when a piston corer is not completely filled with sediment. McManus (1965) equipped a piston corer with a piston deactivator.

Kallstenius (1958) showed that it is advantageous to use a large diameter corer, because inside friction and edge sharpness then have a lesser influence. Richards and Keller (1961) found no evidence of shortening in the top 50 centimeters of cores taken with a large diameter (82 millimeters) hydroplastic gravity corer. Kermabon et al. (1966) designed a wide-diameter piston corer (120 millimeter inside diameter) with a steel barrel and a plastic liner which obtained cores described as having "little or no disturbance" and a gross recovery length close to 100 percent. The longest core obtained was nine meters in length. McManus (1965) developed a 150 millimeter diameter piston coring device with a polyvinylchloride barrel and "no sediment distortion" was observed. The longest core obtained was 2.7 meters.

A corer which generates a sliding liner from its nose to protect and convey the core upward at the rate of penetration decreases the frictional resistance of continuous long cores to a minimum. The Kjellman-Kallstenius corer used in soil engineering has a progressive liner consisting of 16 strips of thin steel wound in small storage chambers in the corer nose. Livingstone (1967) applied this same principle to a standard piston corer, but used Mylar filament tape as the liner. Although the cores obtained were described as "excellent", breakage of the Mylar tape occurred when it came in contact with angular granite granules or coarse sand. Rosfelder and Marshall (1967) used a sleeve of high tensile strength fabric furled in a thin chamber in the corer nose which was pulled up by a piston. Though disturbance was reduced, it was noted that additional methods are needed, particularly for silty and sandy sediments. Rosfelder and Marshall state that the simplest current way to lower external friction in these sediments is by jetting (creating a "water sleeve" on the barrel wall).

Sly (1966) designed a cutter-liner system for soft sediment piston or gravity corers which produces minimum resistance to material entering the barrel. A thin flexible liner made of polythene was obtained in the form of a cylinder closed at one end and was pushed onto the metal sleeve as an inner barrel extension of the core cutter. As the corer penetrates the sediment, material passes upward through the short length of the inner barrel extension of the cutter and then sleeves itself as it rises in the barrel. The inside of the barrel was coated with a lubricant and the rising liner of sediment produced almost no friction against the inner wall of the barrel.

Rosfelder (1966) summarized ways to reduce friction as much as possible:

1. A slow steady penetration speed such as that obtained by hydraulic or pneumatic thrust.

2. A fast single stroke such as that obtained by gravity with free-fall or by implosive reaction, or by explosive reaction.

3. A defined inside clearance or use of a sliding liner.

Emery and Dietz (1941) recognized that the friction of the sediment against the inside of the corer tube could be reduced by use of a smooth liner. They report that cores taken in experiments using celluloid liners were slightly longer than others taken in the absence of a smooth liner. Rosfelder and Marshall (1967) state that the use of a smooth plastic barrel helped to reduce external friction. Hvorslev (1949) suggested that the friction could be reduced by polishing, oiling, or lacquering the sampling tubes. He suggested that future experiments include the determination of the best type of lacquer, enamel or electroplating of liners and tubes to obtain minimum friction, maximum toughness, and maximum protection against corrosion of the tubing.

Civil engineers have made advantageous use of lubricants in conditions similar to those in subsea coring. Terzaghi and Peck (1948) report that friction between concrete and a fairly stiff clay can be reduced by roughly 40 percent by use of a suitable lubricant. A smooth oily surface tough enough not to be rubbed off was used on the concrete caissons for the piers of the San Francisco Bay Bridge.

Leonards (1965) used laboratory measurements to determine coefficients of friction between dry sand and a polished steel rod and compared the results with the steel rod covered with Teflon or graphite. Graphite was found to be an effective lubricant, but Teflon did not perform well.

The present study was conducted to determine whether the penetration of smooth steel into cohesive sediment could be increased through use of a lubricant or polymer coating. Laboratory experiments were conducted under

controlled conditions to measure any differences in penetration among a wide variety of coatings. Experiments at sea were conducted in order to test the most effective lubricants under the conditions found on the ocean floor.

PROCEDURE

<u>Laboratory tests</u>. A series of elimination tests comparing 23 coatings preceded more extensive testing of the six most effective coatings. Either coatings were applied to stainless steel plates, 3 x 12 x 1/8 inches with a 45-degree cutting edge, or plates were fabricated out of the test material. The control was a 16-finish stainless steel plate of the same dimensions.

The sediment used in the laboratory tests was obtained from the Naval Ordnance Test Station (NOTS) Seal Beach Ocean Bottom Simulation Facility. The sediment is a lagoonal mud composed largely of clay and silt sized particles, and has been used extensively in testing by engineers because of its similarity to deep ocean sediments. Muga (1966) summarized the range of some of the characteristics of this sediment and these are presented below:

	Range (from 42 tests)		
	Minimum	Maximum	Average
Vane shear strength (psi)	0.0	1.050	0.530
Remolded strength (psi)	0.0	0.861	0.390
Original water content (%)	43.5	79.6	63.5
Void ratio	1.104	2.126	1.710
Porosity	52.5	68.0	61.9
Liquid limit	41.0	68.0	56.1
Plastic limit	27.5	43.4	34.2
Liquidity index	70	255	136
Percent sand	1.7	25.5	10.2
Percent silt	30.8	54.4	40.5
Percent clay	35.8	66.0	46.4

In obtaining the sediment for these tests, the mud was carefully shoveled into five gallon containers. Any visible organic material was removed. The containers were filled to a depth of approximately 12 inches and a water head of about one inch covered the sediment.

An Atwood machine principle was used as the laboratory test apparatus (Figure 1). A rod, load cell and plate were rigidly connected and were counterbalanced by weights. The rod was allowed to move only vertically

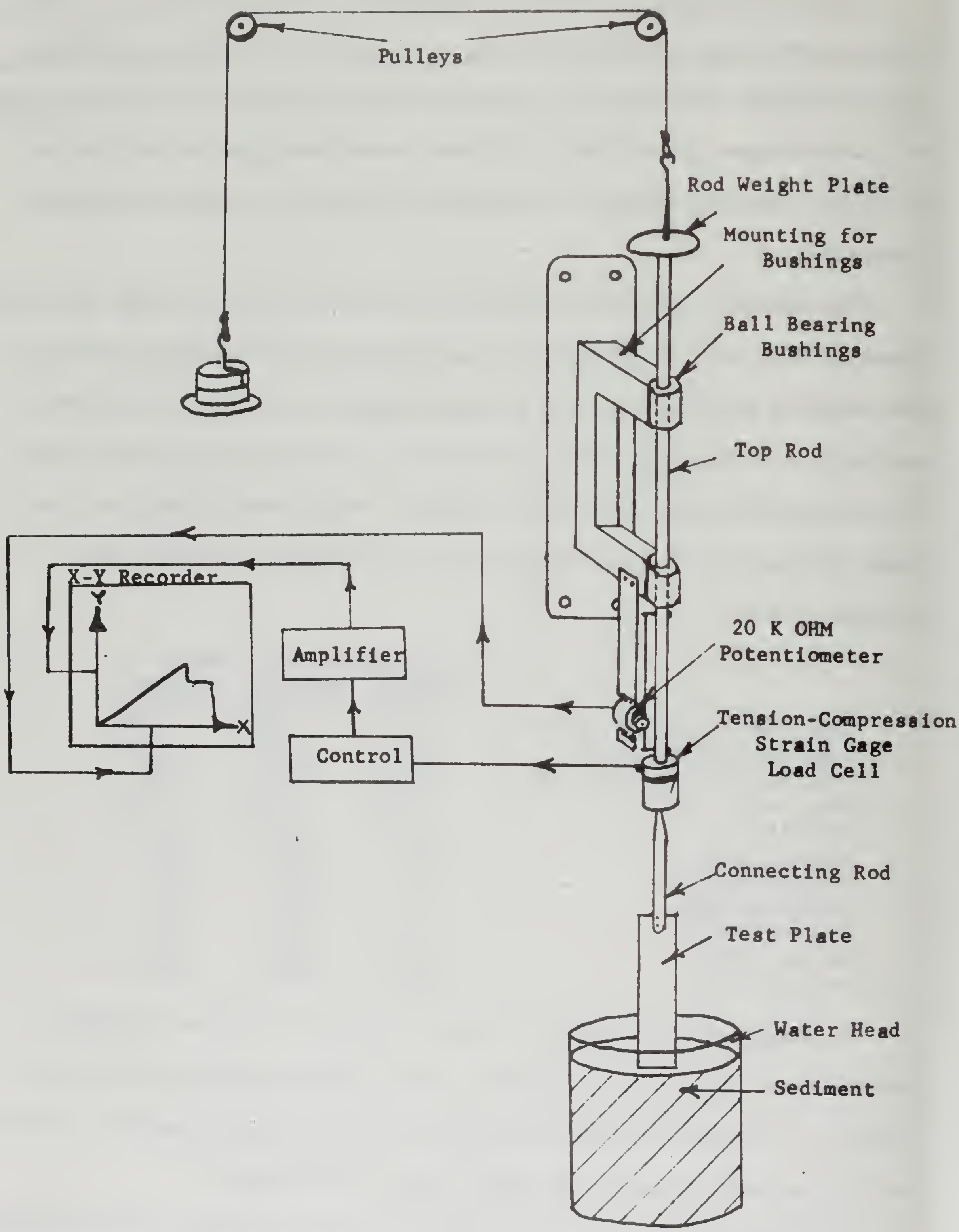

Figure 1. Schematic illustration of laboratory test apparatus

since it was guided by two ball bearing bushings located in a mounting attached to the wall. This insured that the plate would penetrate perpendicular to the sediment surface.

The measuring instruments consisted of a tension-compression load cell and a 20 K ohm potentiometer. The load cell signal, a measure of penetration resistance, was sent to a control panel, was amplified, and then went to the Y axis of the X-Y recorder. To measure penetration the top rod was tapped in two places, 14 inches apart, and a small nut and bolt were placed in each hole. A thin wire was attached to the end of the upper bolt, looped around the potentiometer wheel, and attached to a spring connected to the lower bolt. When the rod moved downward, the potentiometer wheel turned and this signal was sent directly to the X axis of the recorder. The weight of the connecting rod and test plate was zeroed out at the control panel prior to each test.

The balanced rod and plate were lowered vertically to the mud surface and a clamp brake was set. A five pound weight was placed on the rod weight plate, the brake was released, and a stop watch was started. At the end of 60 seconds the five pound weight was removed.

Dynamic penetration was considered to be the rapid penetration produced by the five pound weight accelerating force. Resistance to this force was built up as the plate penetrated the mud, and penetration nearly stopped. In some cases, it did stop. This rapid penetration usually occurred in about half a second. In most cases penetration continued, but at a much slower rate. The total penetration was considered to be all the penetration that occurred in one minute after the start of the test.

An overall view of the test equipment is shown in Plate 1. The load cell with the cover removed is shown in Plate 2. The position of the plate prior to testing is shown in Plate 3 and its position at the end of the test in Plate 4.

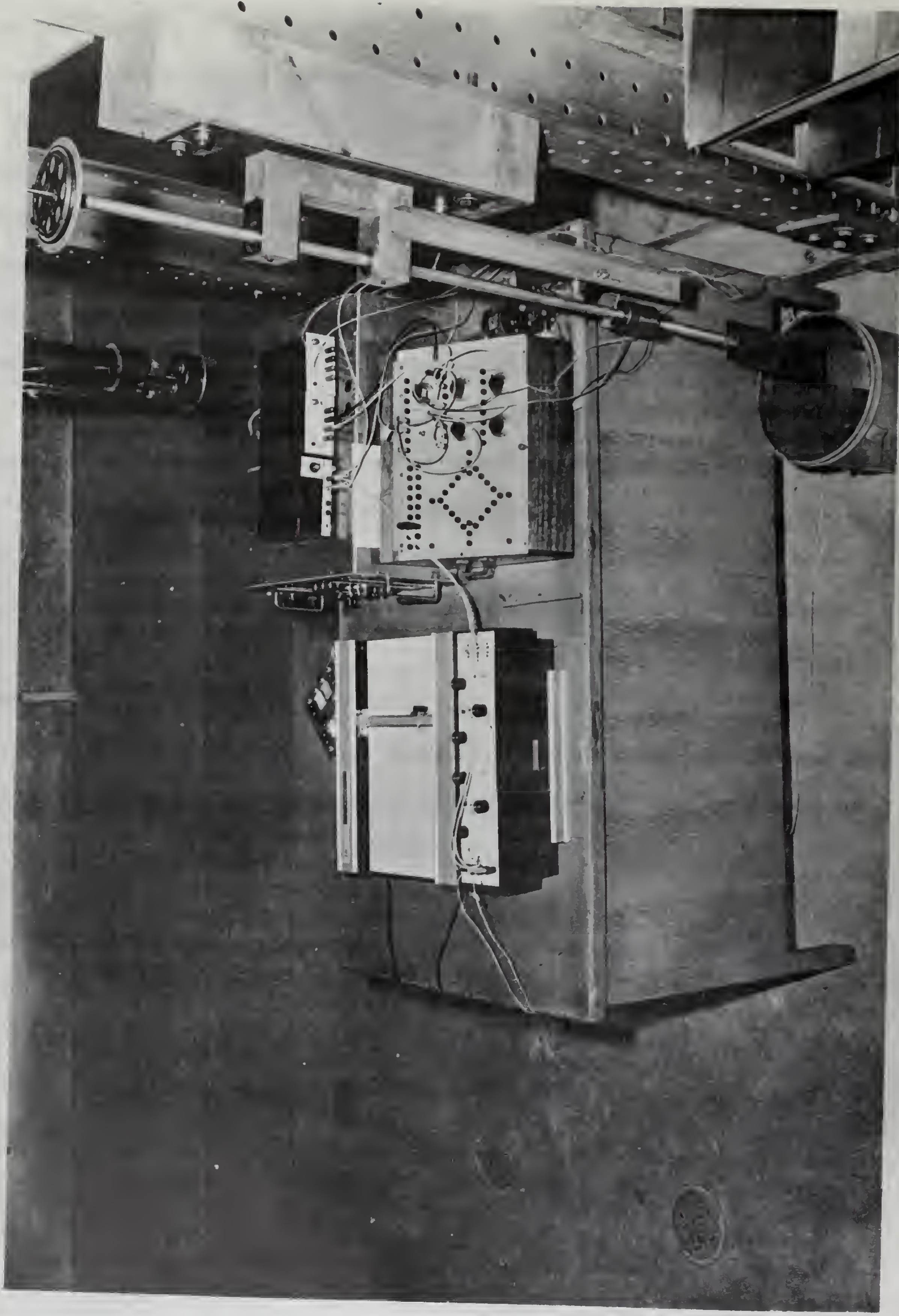

Plate 1. Overall view of laboratory test equipment and apparatus

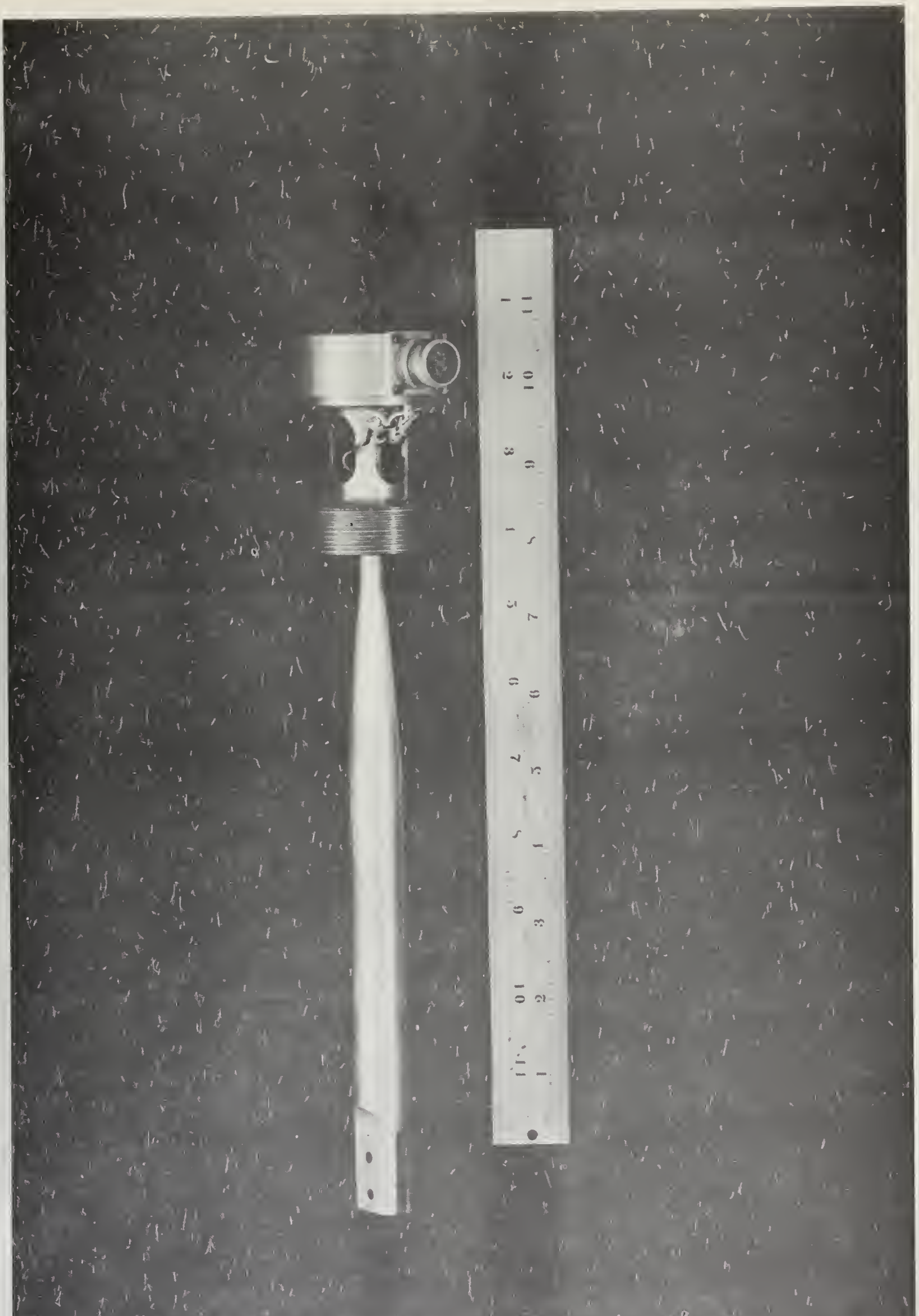

Plate 2. Load Cell with Protective Cover Removed

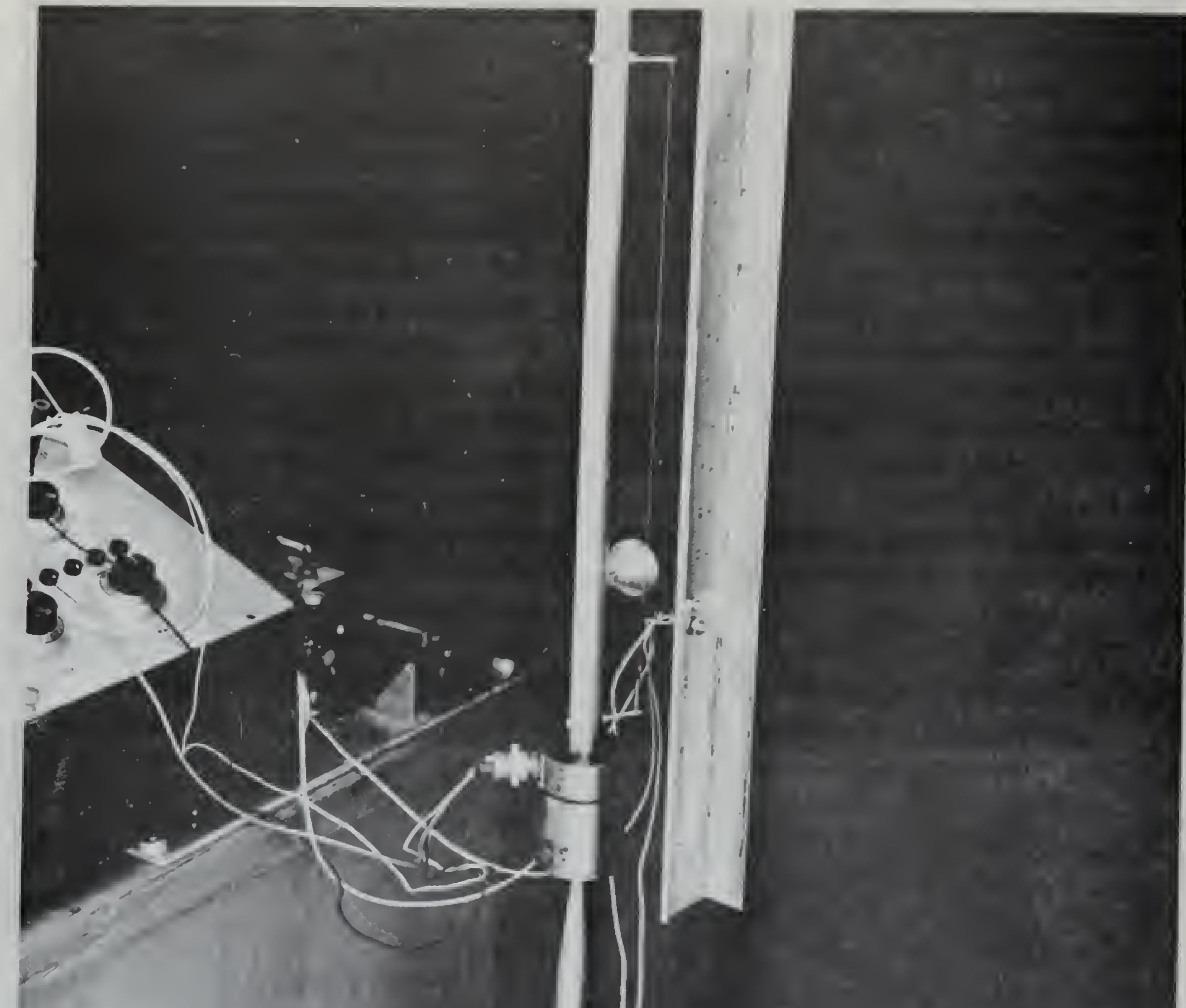

Plate 3. Plate Position at Beginning of Test

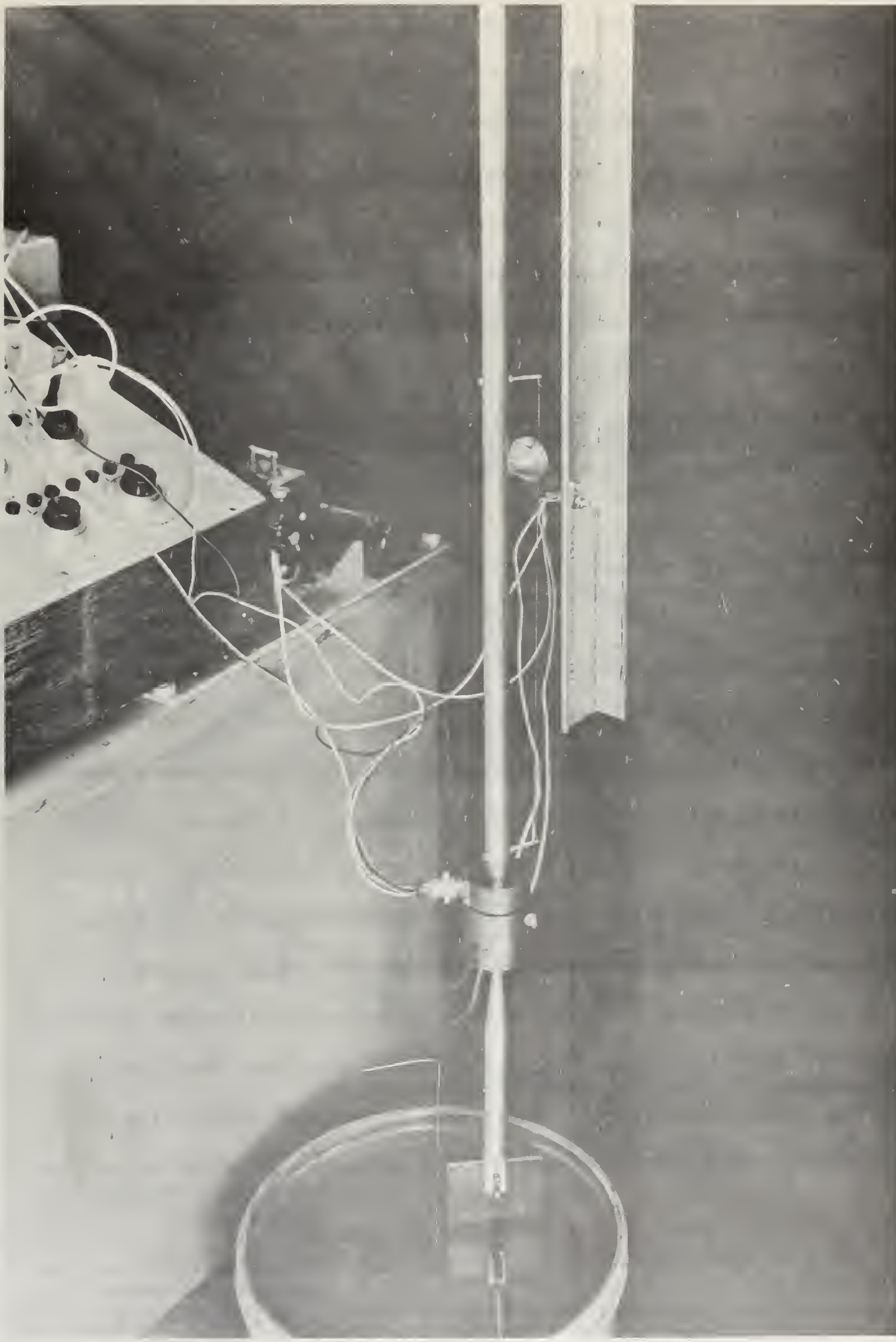

Plate 4. Plate Position at End of Test

To permit maximum use of the sediment and to make the comparative test as valid as possible though the consistency of the sediment might vary, a specific drop pattern was used in each bucket (Figure 2). This allowed over 250 tests to be run in nine buckets. Sixty-eight of the 250 drops were of the control plate.

Twenty-three coatings were tested in a series of elimination tests. Three test plates were compared with two adjacent control plates and the mean values were compared for both dynamic and total penetration. If there was an increase, the percent increase was computed as follows:

$$\text{Dynamic Penetration Increase (DPI)} = \frac{DP_{test} - DP_{control}}{DP_{control}} \cdot 100$$

$$\text{Total Penetration Increase (TPI)} = \frac{TP_{test} - TP_{control}}{TP_{control}} \cdot 100$$

where DP is the dynamic penetration and TP is the total penetration.

The six coatings that showed the greatest increase in penetration in the elimination tests were retested in detail. In the more extensive tests, 12 to 13 test drops were compared with 7 to 8 adjacent control drops, making possible a statistical analysis of the results. When the differences in penetration were found to be statistically significant, additional information was obtained from the penetration resistance diagrams. In addition to penetration, the maximum penetration resistance force, the angle of inclination, and the total work were read directly from the curves of penetration resistance versus penetration (Figure 3).

Maximum Penetration Resistance Force (pounds) - Occurred at the time of maximum dynamic penetration.

Angle of Inclination (degrees) - Measured from the straight section of the penetration resistance curve.

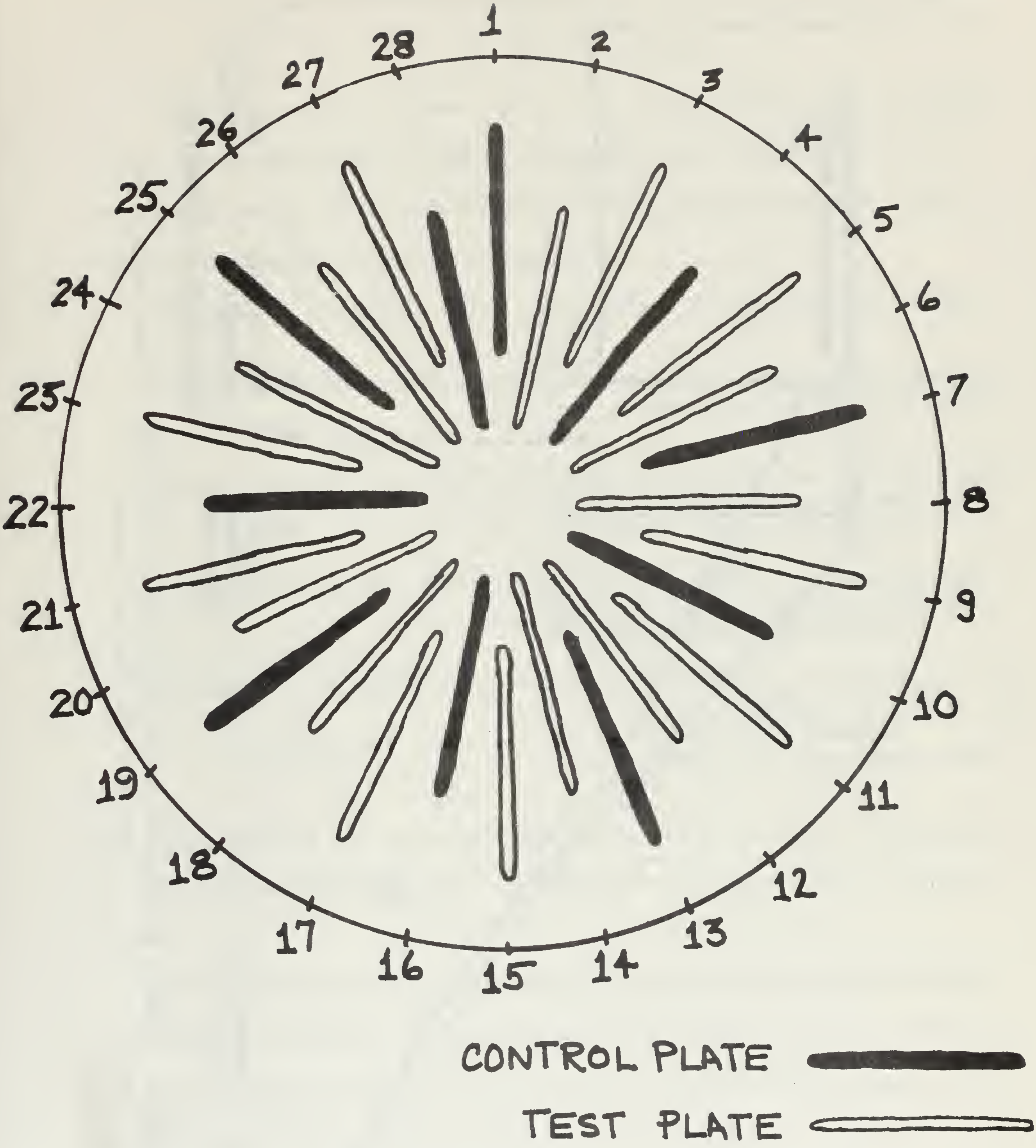

Figure 2. Drop Pattern for Plates into Sediment

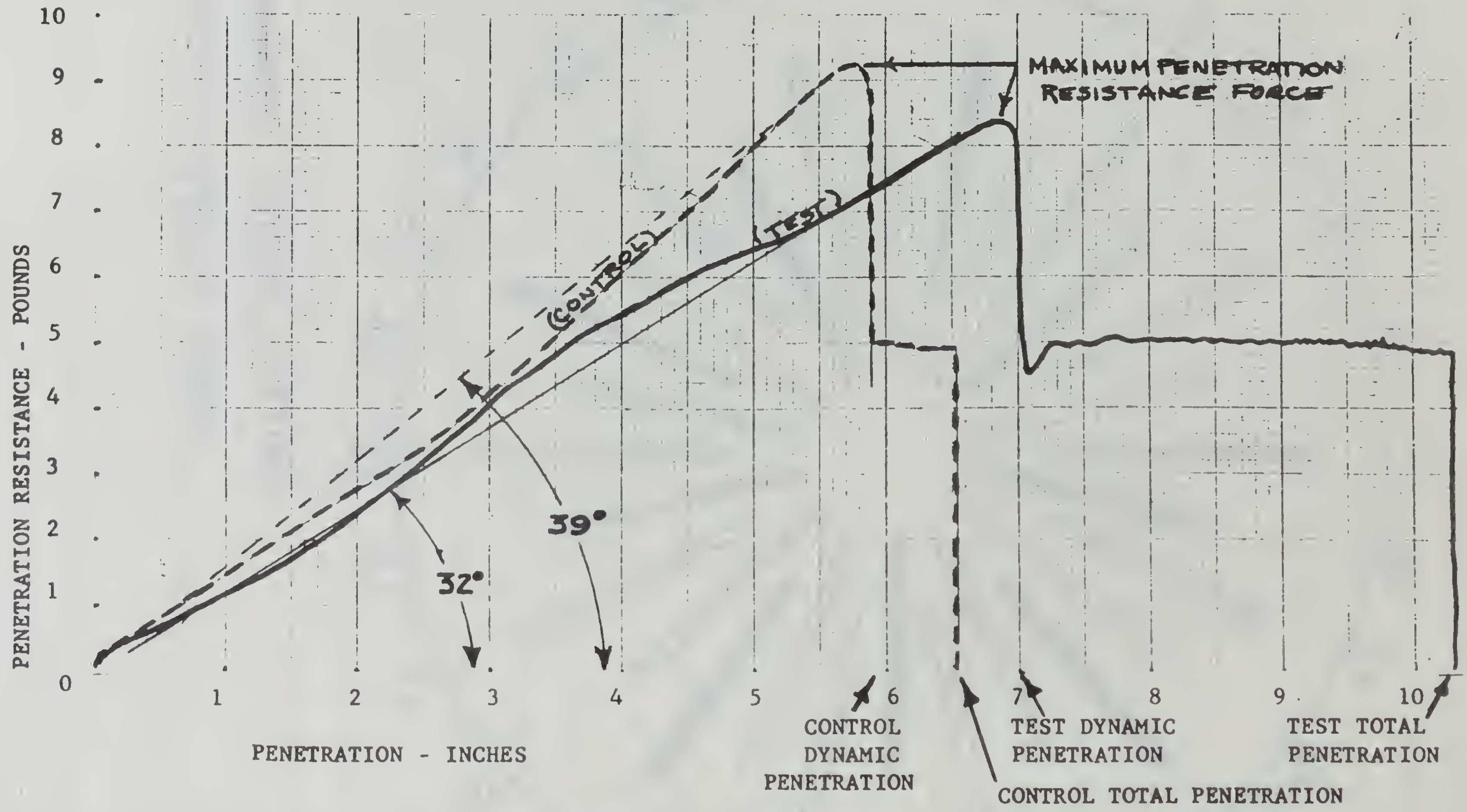

Figure 3. Example Penetration Resistance Diagram Illustrating a Large Difference Between the Test and Control

Total Work (inch-pounds) - The area under the penetration resistance curve; obtained by circumscribing the area recorded for total penetration with a polar planimeter.

The penetration resistance index, the average penetration resistance force, the maximum shear stress, the average shear stress, and percent decrease in average shear stress were computed from the data obtained from the penetration resistance diagrams.

Penetration Resistance Index - The tangent of the angle of inclination.

Average Penetration Resistance Force (pounds) - Computed by dividing the total penetration into the total work.

Maximum Shear Stress (psi) - Computed by dividing the area of dynamic plate penetration into the maximum penetration resistance force.

Average Shear Stress (psi) - Computed by dividing the area of total plate penetration into the average penetration resistance force.

Decrease in Average Shear Stress (%) - $\dfrac{\text{Av. SS}_{\text{control}} - \text{Av. SS}_{\text{test}}}{\text{Av. SS}_{\text{control}}} \cdot 100$
where SS is the shear stress.

Sea Tests. Two of the lubricants that were found to improve penetration in the more extensive laboratory test program were selected for testing at sea.

Fifty cores were taken at sea within the vicinity of Station Three and Station Six (Figure 4). Station Three has a depth of 250 to 260 feet, and the sediment consists of very fine sand with about five percent clay. The particles have a median diameter of 3.20 phi units. A phi unit is the negative logarithm to the base two of the particle diameter in millimeters divided by one millimeter. Station Six has a depth of 280 to 300 feet and the sediment consists of very fine silt with about 35 percent clay. The particles have a median diameter of 7.05 phi units.

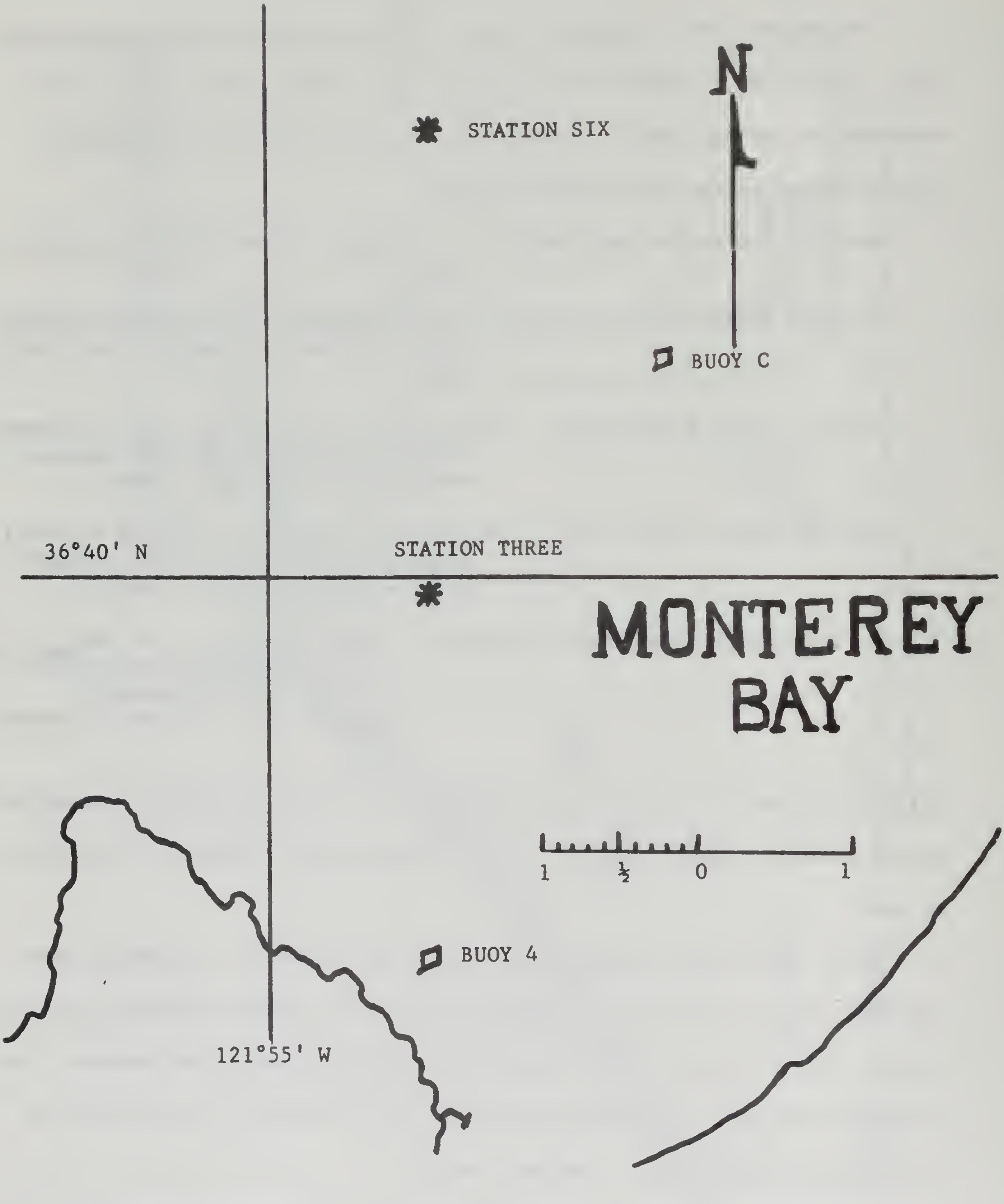

Figure 4. Locations of sea tests.

A Phleger corer with a two-foot barrel and liner (I.D. 1.4 inches, O.D. 1.6 inches) was used during the first test at sea. Burns (1966) found that the optimum free-fall setting for small light-weight gravity corers not fitted with stabilizing fins was two to three meters. Corers equipped with stabilizing fins maintained a vertical position over free-fall distances of as much as 25 meters. In the present study a corer with fins was used and the free-fall setting was five meters.

The corer was lowered to approximately five meters from the bottom and allowed to free-fall until the corer hit the bottom, at which time the stop watch was started and additional line payed out to prevent the drift of the ship from prematurely pulling out the corer. After one minute the corer was retrieved and penetration was recorded. Since sediment particles became embedded in the lubricant, outside penetration was measured by noting the highest mark on the lubricated barrels, but a one-fourth-inch strip of adhesive tape was secured lengthwise to the uncoated barrel to ensure an accurate measurement. Inside penetration was measured by lowering a rod into the barrel from the top of the corer tube.

Since four of the lubricated corer drops penetrated up to the bulb weight, it was apparent that a longer corer barrel would be necessary if a true picture of penetration differences were to be obtained. Also, sediment variation caused by drift from one drop to the next seemed to account for a large variation in the results.

A light-weight aluminum I beam three feet in length with two Phleger corers attached at each end by four and one half feet of nylon line was used during the second set of tests at sea (Figure 5). This apparatus enabled dropping a coated and uncoated corer at the same time and helped to reduce the variation caused by drifting. A new barrel three feet long

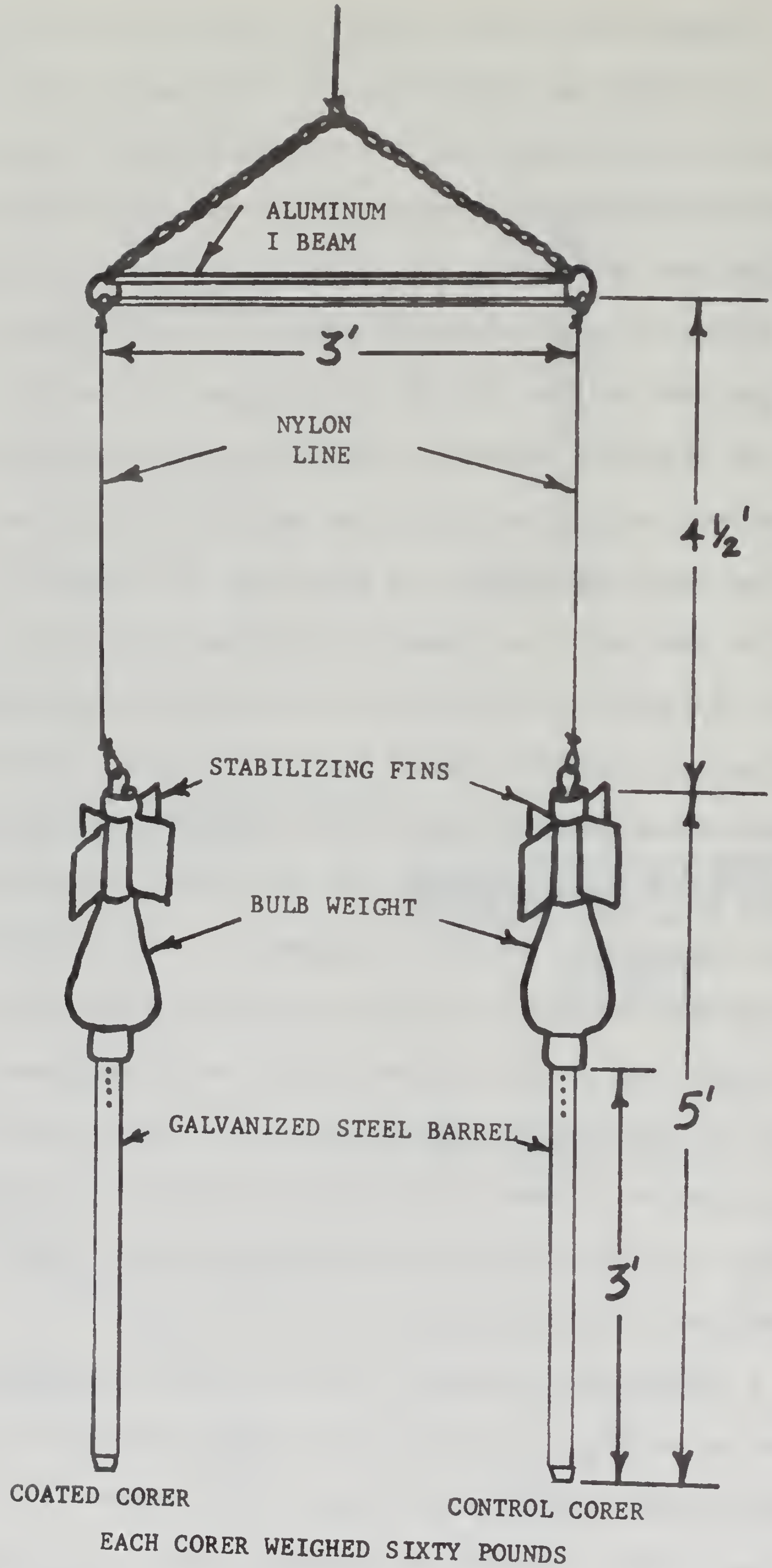

Figure 5. Dual corer sea test apparatus.

(I.D. 1.6 inches, O. D. 1.9 inches) fabricated out of galvanized pipe was used without a liner. Twelve three-eighth-inch holes were drilled in the upper end of the barrel to allow additional water to escape during penetration. A core catcher was not used in either sea test.

RESULTS AND DISCUSSION

Laboratory tests. A large increase in penetration was apparent for some of the coatings when coated plates were compared to control plates. Figure 3 illustrates a large difference in dynamic and total penetration between a lubricated test plate and the control plate. Figure 6 illustrates a smaller difference in penetration.

Table 1 presents the coatings which showed little or no increase in penetration when the test plates were compared to the control plate in the elimination tests. The following gives a brief description of each of these coatings:

1. Polypropylene - A coating resin with low frictional resistance; applied by using conventional air spray atomization spray equipment and baking at 400 degrees Fahrenheit for 10 minutes; manufactured by SCM Glidden-Durkee Division, Cleveland, Ohio.
2. Polysulfide Liquid Polymer/Epoxy Resin System (T-140-26) - A low frictional resistance, tough, flexible coating; applied by brushing on the plates and air-drying for seven days; manufactured by Thiokol Chemical Corporation, Trenton, New Jersey.
3. Neoprene (N-29) - A two-component bonded coating that has a high adhesive value and a high abrasive resistance; applied by brushing on the plates and air-drying for three days; manufactured by Gaco Western, Incorporated, Seattle, Washington.
4. Teflon repair coating (Ply) - A liquid polymer system in an aerosol spray container; applied by spraying on the plates and baking at 475 degrees Fahrenheit for 45 minutes; manufactured by National Chemical Laboratories Incorporated, Lodi, New Jersey.

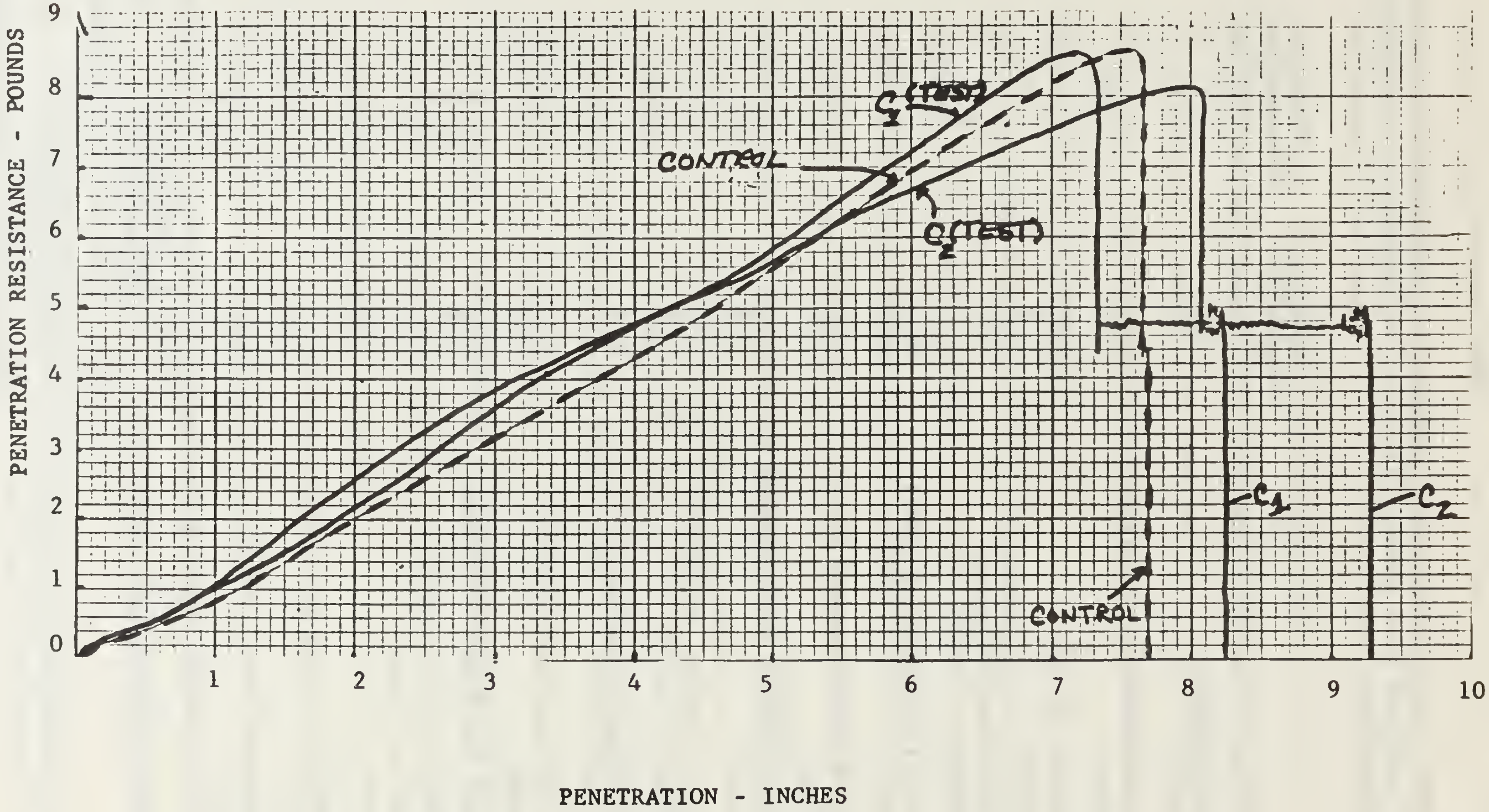

Figure 6. Penetration Resistance Diagram Illustrating a Small Difference Between the Test and Control

TABLE 1

Dynamic penetration, total penetration and percent penetration increases for coatings that showed little or no increase in penetration over the control plate.

Plate	Dynamic Penetration (in)	Total Penetration (in)	DPI[1] (%)	TPI (%)
Polypropylene	7.1	7.1		
Control	7.3	7.5		
Polysulfide (epoxy resin)	7.2	7.4		
Control	7.1	7.2		
Neoprene (N-29)	7.7	7.7		
Control	7.2	7.3		
Teflon Repair Coating	7.7	8.7		
Control	8.1	8.7		
Solid Film Lubricant (66S)	8.4	8.4		
Control	8.6	9.5		
Solid Film Lubricant (77S)	10.0	10.0	4	
Control	9.6	10.2		
Silicon Grease (consistency 3)	8.2	8.2		
Control	8.1	8.5		
Graphite Grease (consistency 4)	5.3	6.5		
Control	5.3	6.4		
Lime Grease (consistency 4)	4.5	6.1		
Control	4.6	5.9		
Soda Grease (consistency 4)	6.1	6.1		
Control	5.9	7.1		
Bonded Lubricant (Dow Corning 3400)	8.8	10.0	11	
Control	7.9	10.6		
Graphite Flakes	7.9	8.9		7
Control	7.8	8.3		
Paraffin	9.0	9.9	11	10
Control	8.1	8.2		
Plexiglass	8.2	9.3	8	4
Control	7.6	8.9		

[1]Dynamic Penetration Increase $= \frac{DP(test) - DP(control)}{DP(control)} \cdot 100$

where DP is the dynamic penetration.

[2]Total Penetration Increase $= \frac{TP(test) - TP(control)}{TP(control)} \cdot 100$

where TP is the total penetration.

5. Solid Film Lubricant (66S) - A molybdenum disulfide film lubricant; the manufacturer applied this lubricant by either spraying or dipping it on the plates and air drying; manufactured by Electrofilm, Incorporated, North Hollywood, California.

6. Solid Film Lubricant (77S) - A coating which contains molybdenum disulfide and graphite; the manufacturer applied this lubricant by spraying then setting the resin by heat; manufactured by Electrofilm, Incorporated.

7. Silicon grease (consistency 3) - A grease with a silicon thickener; applied by spraying a thin film on the plates; manufactured by Permatex, Incorporated, West Palm Beach, Florida.

8. Graphite grease (consistency 4) - A grease with a graphite thickener; applied by rubbing a thin film on the plates; manufactured by American Oil Company, Chicago, Illinois.

9. Lime grease (consistency 4) - A grease with a lime thickener; applied by rubbing a thin film on the plates; manufactured by American Oil Company.

10. Soda grease (consistency 4) - A grease with a calcium carbonate thickener; applied by rubbing a thin film on the plates; manufactured by American Oil Company.

11. Bonded lubricant (Dow Corning 3400) - A bonded lubricant recommended where environments are dirty and abrasive; applied by brushing on the plates and baking at 400 degrees Fahrenheit for one hour, difficult to apply evenly; manufactured by Dow Corning Corporation, Midland, Michigan.

12. Graphite flakes - Applied by rubbing on the plates. A previous experiment by Leonards (1965) showed graphite flakes to be an effective lubricant between smooth steel surfaces and dry sand.

In the wet sediment of the present experiment, the flakes were not effective.

13. Paraffin - Applied by gluing wax paper to plates. Though this method assured and even coat of wax, it was found to be unsatisfactory since the paper began to loosen in the wet sediment.

14. Plexiglass - Plates fabricated out of plexiglass were tested, but penetration was not much greater than the control plate in spite of its smooth surface.

Table 2 presents the coatings that increased penetration sufficiently to be worthy of further consideration. The following gives a brief description of these coatings:

1. CRC - An inexpensive, rust preventative, moisture displacing lubricant; easily applied by spraying from an aerosol can; manufactured by CRC Chemicals, Division of C. J. Webb, Incorporated; Dresher, Pennsylvania.

2. STP - (Scientific Treated Petroleum) - An inexpensive thick oil; was easily applied by rubbing on the plates; manufactured by the STP Corporation, Des Plaines, Illinois.

3. Zinc grease (consistency 4) - A grease with a zinc thickener; applied by rubbing on the plates; manufactured by American Oil Company.

4. Lithium grease (consistency 2) - A grease with a lithium thickener; applied by rubbing on the plates; manufactured by American Oil Company.

5. Teflon tape (S-16) - A fluorocarbon resin, a white solid plastic with an inherent anti-stick property; purchased on tape with an adhesive backing, cut to size and applied to steel plates;

TABLE 2

Dynamic penetration, total penetration and percent penetration increases for coatings that showed considerable increase over the control plate.

Plate	Dynamic Penetration (in)	Total Penetration (in)	DPI[1] (%)	TPI[2] (%)
CRC	4.8	6.5	5	44
Control	4.0	4.5		
CRC (repeat test)	6.9	9.4	21	42
Control	5.7	6.7		
STP	6.2	9.4	5	40
Control	5.9	6.7		
Zinc Grease (consistency 4)	6.0	8.1	11	35
Control	5.4	6.0		
Lithium Grease (consistency 2)	4.6	5.4	15	35
Control	4.0	4.0		
Teflon Tape (S-16)	6.9	9.7	10	33
Control	6.3	7.3		
Teflon Tape (S-16) (repeat test)	7.5	9.6	6	26
Control	7.1	7.6		
FEP Film	7.2	8.8	18	22
Control	6.1	7.2		
Teflon S	6.1	8.7	--	13
Control	6.1	7.7		
Teflon S (repeat test)	8.7	10.5	9	15
Control	8.0	9.1		
Oil Impregnated Bronze	8.3	8.3	25	--
Control	6.6	8.5		
Nylon Tape (S-18)	6.4	9.5	--	20
Control	6.5	7.9		

[1]Dynamic Penetration Increase $= \dfrac{DP(test) - DP(control)}{DP(control)} \cdot 100$

where DP is the dynamic penetration.

[2]Total Penetration Increase $= \dfrac{TP(test) - TP(control)}{TP(control)} \cdot 100$

where TP is the total penetration.

manufactured by E. I. Dupont De Nemours & Company, Incorporated, Wilmington, Delaware.

6. FEP film - A new form of Teflon, strong, abrasion resistant, and non-hydroscopic; purchased on tape with an adhesive backing, cut to size and applied to steel plates; manufactured by Dupont.

7. Teflon S - A teflon formulated for toughness and abrasion resistance, more durable than the teflon used in cookware if used at low temperatures, but cannot withstand high heat; the manufacturer, Dupont, applied this coating to plates of the desired dimensions.

8. Oil impregnated bronze (Oilite) - A self lubricating product made from powdered metal and 18 percent oil by volume, the oil exudes under pressure; the manufacturer prepared the plate; manufactured by Amplex Division, Chrysler Corporation, Detroit, Michigan.

9. Nylon tape (S-18) - A strong, smooth coating; purchased on tape with an adhesive backing, cut to size and applied to steel plates; manufactured by Dupont.

Table 2 shows that in the elimination tests CRC, STP, zinc grease, lithium grease, and Teflon (S-16) all increased total penetration 30 to 40 percent, while FEP film, Teflon S, oil impregnated bronze, and nylon increased penetration from 15 to 20 percent. The limited quantity of sediment restricted extensive testing to six selected coatings, though all of these merit further consideration.

The results of the more extensive tests along with the statistical analysis are presented in Table 3. STP increased total penetration by 46 percent, CRC by 25 percent, zinc grease by 24 percent, and lithium grease by 20 percent. All of these increases are highly significant. Dynamic

TABLE 3

Dynamic penetration, total penetration, and percent penetration increases for six coatings selected for extensive tests and the results of a statistical analysis.

Plate	No. of Drops	DP[1] (in)	TP[2] (in)	"t" Value	Level of Significance	DPI[3] (%)	TPI[4] (%)
STP	13	6.7 ± 0.2[5]	9.9 ± 0.4	Dyn.--	Not Significant	12	46
Control	8	6.0 ± 0.6	6.8 ± 0.7	Tot.=3.9	P = .005		
CRC	12	7.9 ± 0.3	9.9 ± 0.7	Dyn.--	Not Significant	13	25
Control	8	7.0 ± 0.5	7.9 ± 0.5	Tot.=4.0	P = .005		
Zinc Grease	12	8.5 ± 0.4	10.3 ± 0.7	Dyn.--	Not Significant	9	24
Control	7	7.8 ± 0.4	8.3 ± 0.5	Tot.=4.1	P = .005		
Lithium Grease	12	8.1 ± 0.2	9.2 ± 0.2	Dyn.=2.1	P = .05	7	20
Control	7	7.6 ± 0.1	7.7 ± 0.2	Tot.=5.5	P = .005		
Teflon Tape (S-16)	12	8.1 ± 0.4	9.1 ± 0.2	Dyn.--	Not Significant	2	8
Control	7	7.9 ± 0.5	8.4 ± 0.6	Tot.--	Not Significant		
FEP Film	12	8.2 ± 0.3	8.6 ± 0.4	Dyn.--	Not Significant	5	--
Control	8	7.8 ± 0.3	8.5 ± 0.3	Tot.--	Not Significant		

[1] DP is the dynamic penetration.

[2] TP is the total penetration.

[3] Dynamic Penetration Increase $= \dfrac{DP(test) - DP(control)}{DP(control)} \cdot 100$

[4] Total Penetration Increase $= \dfrac{TP(test) - TP(control)}{TP(control)} \cdot 100$

[5] Mean $\pm$ Standard Error.

penetration increases were much smaller (7 to 13 percent) and were not statistically significant with the exception of lithium grease.

Since dynamic penetration was only slightly increased by the use of lubricants, while the slower penetration that occurred in about one minute was increased considerably, it appears that it would be advantageous to allow lubricated corers to remain at least a minute after hitting the ocean floor. This finding can be explained more thoroughly by referring to use of available energy. Rosfelder (1966) stated that corer penetration is controlled by the available energy and that penetration ceases when the frictional resistance becomes higher than the available energy. In the laboratory tests of the present study the available energy was the same for all the plates at the beginning of the test. At the end of dynamic penetration the available energy used was about the same for both the test and control plates. However during the slower penetration which followed dynamic penetration, the lubricated plates were able to use the available energy more effectively than the control plates. The lubricated plates were able to overcome the frictional force and continued to penetrate the sediment; therefore a striking increase was noted if total penetration was considered. Several factors may have contributed to the relatively small increase in dynamic penetration: (a) during dynamic penetration the penetrated surface area was small and therefore the frictional force was not fully developed, (b) the higher water content in the surface layers of the sediment did not create as much frictional resistance, (c) during rapid penetration the accelerating force may have overcome the frictional force to such an extent that the effectiveness of the coating was not apparent.

The results of Teflon tape and FEP film presented on Table 3 are quite different from the results of the elimination tests; the small increases

noted in the extensive tests are not significant. Unfortunately the adhesive of the tapes began to loosen slightly around the edges and penetration was retarded. Though the tapes are probably not suited for a corer, these finishes can be thermally bonded to metal. FEP film can be obtained as a tubing in thicknesses up to 90 mils; and therefore might be suitable as a corer liner. This type of coating would be advantageous because it would not contaminate the sediment sample and would not need to be reapplied. Leonards (1965) tested Teflon tape as a lubricant between fine grained dry sand and smooth stainless steel, but it was not found to be effective. There was no mention of the tape loosening as it did in the wet environment of the present study.

Table 4 presents the maximum penetration resistance force, the angle of inclination, the penetration resistance index, the total work, the average penetration resistance force, the maximum shear stress, the average shear stress, and the percent decrease in average shear stress when STP, CRC, zinc grease or lithium grease were applied to the plates.

The maximum and average penetration resistance forces were about the same for the control and lubricated plates. However these forces occurred at greater plate penetration for the lubricated plate; therefore the resistance force per unit area was lower for lubricated plates than it was for the control plates.

The measured penetration resistance index (the tangent of the angle of inclination) is presented in Table 4 next to a computed value of this index. Hvorslev (1949) developed these terms while working with penetration resistance diagrams. He stated that after initial resistance the slope of the straight sections of the curve was governed by wall friction. He felt that for a coring sampler without too heavy walls or excessive inside and outside clearances, the penetration resistance and the corresponding density, consistency, or strength of the soil can be represented by a

TABLE 4

Penetration resistance, angle of inclination, penetration resistance index, total work, shear stress, and percent decrease in shear stress of four lubricants selected for extensive tests.

Plate	No. of Drops	Maximum Penetration Resistance (lb)	Angle of Inclination (degree)	PRI[1]	Computed PRI[2]	Total Work (in-lb)[3]	Average Penetration Resistance (lb)	Maximum Shear Stress (psi)	Average Shear Stress (psi)	Decrease in Av. Shear Stress (%)[4]
STP	13	8.8	34	1.36	1.31	45.2	4.6	0.21	0.073	34
Control	8	8.6	38	1.46	1.44	30.6	4.5	0.24	0.11	
CRC	12	8.5	31	1.20	1.08	45.2	4.6	0.19	0.075	21
Control	8	8.6	33	1.30	1.22	35.6	4.5	0.21	0.095	
Zinc Grease	12	8.6	29	1.10	1.02	47.6	4.6	0.17	0.073	19
Control	7	9.1	32	1.26	1.16	38.2	4.6	0.19	0.090	
Lithium Grease	12	8.6	29	1.10	1.06	42.0	4.6	0.17	0.080	10
Control	7	8.7	31	1.20	1.14	34.0	4.4	0.18	0.091	

[1] PRI (Penetration Resistance Index) = Tangent of angle of inclination (The PRI values above were multiplied by two because the Y axis unit scale was ½ that of the X axis).

[2] $\text{Computed PRI} = \dfrac{\text{Maximum Penetration Resistance (lb)}}{\text{Dynamic Penetration (in)}}$

[3] $\text{Average Penetration Resistance} = \dfrac{\text{Total Work (in-lb)}}{\text{Total Penetration (in)}}$

[4] $\text{Decrease in Average Shear Stress (\%)} = \dfrac{\text{Av. SS control} - \text{Av. SS test}}{\text{Av. SS control}} \cdot 100$, where SS is the Shear Stress.

penetration resistance index equal to the tangent or tangents of the angles of inclination of the straight sections of the penetration resistance diagram. Hvorslev also suggested that in uniform soil it would suffice to determine the maximum penetration resistance and to divide by penetration in order to obtain a penetration resistance index. The latter method would be advantageous for determining the penetration resistance index of ocean sediments in situ.

In the present study the computed value was obtained by dividing the maximum penetration resistance in pounds by the dynamic penetration in inches. The measured penetration resistance index was obtained by multiplying the tangent of the angle of inclination by two since the Y axis scale was one-half that of the X axis. The measured and computed values presented in Table 4 are in good agreement.

Total work accomplished was higher when plates were lubricated. The larger the total work, the more effective the use of available energy.

The maximum and average shear stress were lower for lubricated plates than for the uncoated control plates. The decrease in average shear stress through use of lubricants ranged from 10 to 34 percent.

The maximum shear stress and resistance per unit length values obtained in the present study compare well with the values reported by Wilson (1961). Wilson used a pullout steel pipe in a horizontal cylinder apparatus to estimate the frictional properties of a cohesive clay (moisture content 68 percent) taken from the boring sites in the Gulf of Mexico. The liquid limits were 44 to 108, the plastic limits were 20 to 30, and the plastic indexes were 10 to 83. A pulley and weight arrangement was used to extract the embedded pipe (O.D. 2-3/8 inches) and shear stress versus the longitudinal pipeline movement were recorded. Ultimate shear stress, the maximum shear stress encountered during the extraction tests,

was found to be 0.14 to 0.15 pounds per square inch. His results were in fair agreement with the cohesion found from Mohr circle stress analysis of the same sediment. The latter was determined at the boring site by using special large strain quick-triaxial shear tests. Ultimate shear stress appeared to be independent of the embedment duration since the shear stress was about the same when tests were conducted one or sixteen hours after insertion of the pipe. Wilson assumed that the resistance per unit length (q), was directly proportional to the maximum shear strength (Tm) of the clay near the mud line (within 1½ feet of the surface). Thus; q = p Tm, where p is the perimeter of clay/pipe boundary.

Wilson's Ranges (four horizontal pullout tests)	Present Study (30 vertical penetration tests)
Tm = 0.14 to 0.15	Tm = 0.19 to 0.24 (these values are from control plate data)
$p = \pi \cdot D$ $= \pi \cdot 2\text{-}3/8$ in	p = 3 + 3 + 1/8 + 1/8
p = 7.45 in	p = 6.25 in
q = 1.04 to 1.12$(\frac{lb}{in})$	q = 1.19 to 1.50 $(\frac{lb}{in})$

Since the above data agrees fairly well, it appears that near the surface of the sediment the maximum shear stress and resistance per unit length are independent of the method of applied force, i.e., pullout or penetration, horizontal or vertical.

Muga (1966) conducted vertical pullout tests with flat plates at the NOTS Seal Beach Ocean Bottom Simulation Facility. Tongue and groove steel sheet piling 24 inches wide and cut in lengths of 4, 8, and 16 feet were inserted until the upper edge was flush with the mud surface. Embedment duration periods ranged from 25 minutes to 72 hours. Breakout force was recorded and then divided by surface area.

The maximum shear stress developed for the four-foot plates during the various embedment periods was 0.42 pounds per square inch. This value

is an average of five vertical pullout tests. The values obtained for the four-foot plates were chosen since the sediment used in the present study was obtained from the same mud pit within two feet of the surface. The maximum shear stress developed in the present study was 0.21 pounds per square inch. This value is an average of 30 vertical penetration tests conducted with a 16-finish stainless steel plate. Since the shear stress reported by Muga is double that found in the present study, it appears that greater force would be required to pull out plates than to drive them in. It is possible that the four-foot depths used in Muga's study accounted for the twofold difference since the sediment would be firmer and of a lower moisture content than it would be at the one foot depths used in the present study. However pullout tests are known to require additional force to overcome the partial vacuum created below the embedded object during withdrawal and the weight of material adhering to the object. Since shear stress can be reduced by the use of coatings or lubricants, it would appear that it would be advantageous to use coatings for extractions of metal surfaces from cohesive sediments.

Sea tests. The two lubricants selected for testing at sea were STP and zinc grease. Though CRC improved penetration in the laboratory tests slightly more than zinc grease, the manufacturer indicated that CRC contained a surfactant that caused the product to emulsify when contaminated with 10 percent water and that it probably would not remain on the corer barrel during a free-fall through sea water. However, one drop was made using a corer barrel coated with CRC mixed with a red dye and it was still on the barrel after a fall through 200 feet of water.

The results of Sea Tests I and II are presented on Table 5. During Sea Test I (conducted with the Phleger corer and two-foot barrel) eight drops of the STP-coated barrel and five drops of the uncoated barrel were

TABLE 5

Outside and inside penetration and percent penetration increase of two lubricants selected for sea tests and the results of a statistical analysis.

Test & Location	Core Coating	No. of Drops	OP[1] (in)	IP[2] (in)	OPI[3] (%)	IPI[4] (%)	"t" Value Level of Significance
Sea Test I (Station 6)	STP	8	22.0 ± 0.8[5]	13.8 ± 1.6	12	6	Not Significant
	Control	5	19.6 ± 2.0	13.0 ± 2.0			
Sea Test II (Station 6)	STP	9	38.2 ± 1.1	26.6 ± 0.7	18	16	Out.=3.0 P=.005
	Control	9	32.4 ± 1.5	23.0 ± 0.6			In.=3.7 P=.005
Sea Test II (Station 3)	STP	2	22.3	13.3	35	13	
	Control	2	16.5	11.8			
Sea Test II (Station 3)	Zinc Grease	6	20.4 ± 1.7	11.3 ± 1.0	18	3	Not Significant
	Control	6	17.3 ± 2.3	11.0 ± 1.4			

[1]OP is the outside penetration.

[2]IP is the inside penetration.

[3]Outside Penetration Increase = $\dfrac{\text{OP(test)} - \text{OP(Control)}}{\text{OP(control)}} \cdot 100$

[4]Inside Penetration Increase = $\dfrac{\text{IP(test)} - \text{IP (Control)}}{\text{IP(control)}} \cdot 100$

[5]Mean $\pm$ Standard Error.

made in the vicinity of Station Six. Though there was an increase in mean penetration when STP was on the barrel, the results were not statistically significant due to the large error produced by the varying sediment. Also during Sea Test I the velocity of the wind was three to four meters per second and the ship drifted considerably. Richards and Keller (1961) found that a corer with a large-diameter (82 millimeter) lightweight barrel (PVC) towed in a position inclined to the vertical whenever the ship drifted with wind speeds of more than a few meters per second and cores were unobtainable. Though the present study employed a small-diameter steel barrel, perhaps corer penetration was lower and more variable due to the non-vertical entrance angle during Sea Test I. In addition, the difference in the mean penetration was not as great as it would have been had a longer barrel been used, since four of the drops made with the STP-coated barrel penetrated up to the bulb weight and none of the drops made with the uncoated barrel penetrated that far.

During Sea Test II (conducted with the dual corer apparatus with three-foot barrels) nine comparative drops were made and the increases in both inside and outside penetration were highly significant (P = .005). The percentage increase of 18 percent is probably conservative since the STP-coated barrel again penetrated up to the blub weight in six out of nine drops. For this reason two additional drops were made at Station Three which has a firmer sediment. The percentage difference in outside penetration between the STP-coated barrel and the uncoated barrel increased to 35 percent. This percent increase in penetration is similar to that obtained in the laboratory.

Since one of the three-foot barrels was lost, zinc grease was tested on the two-foot Phleger barrels. Although the outside penetration was increased by 18 percent, the results were not statistically significant,

perhaps because only six drops were made. Also, two of the six drops made with the zinc grease coated barrel penetrated up to the bulb weight and none of the uncoated barrels penetrated that far.

Both STP and zinc grease remained on during free-fall and after penetration. There was still a film of STP and zinc grease on the cutting edge of the corer after the mud was removed.

Gross recovery length of cores was increased by the use of STP lubricant. Since a core catcher was not used perhaps the inside penetration measurements are not valid. However Figure 7 shows the outside penetration and inside penetration data recorded during Sea Test II using STP-coated and uncoated barrels at Station Three and Station Six. A 60 to 70 percent recovery ratio was obtained for both the coated and uncoated barrels. Emery and Hulsemann (1964) using standard pipe with diameters of 30 to 36 millimeters (1½ to 2 inches) obtained core lengths of about 50 percent of the total penetration when penetration ranged from one to four meters. Their tests were also conducted in the ocean with gravity corers in silty clay.

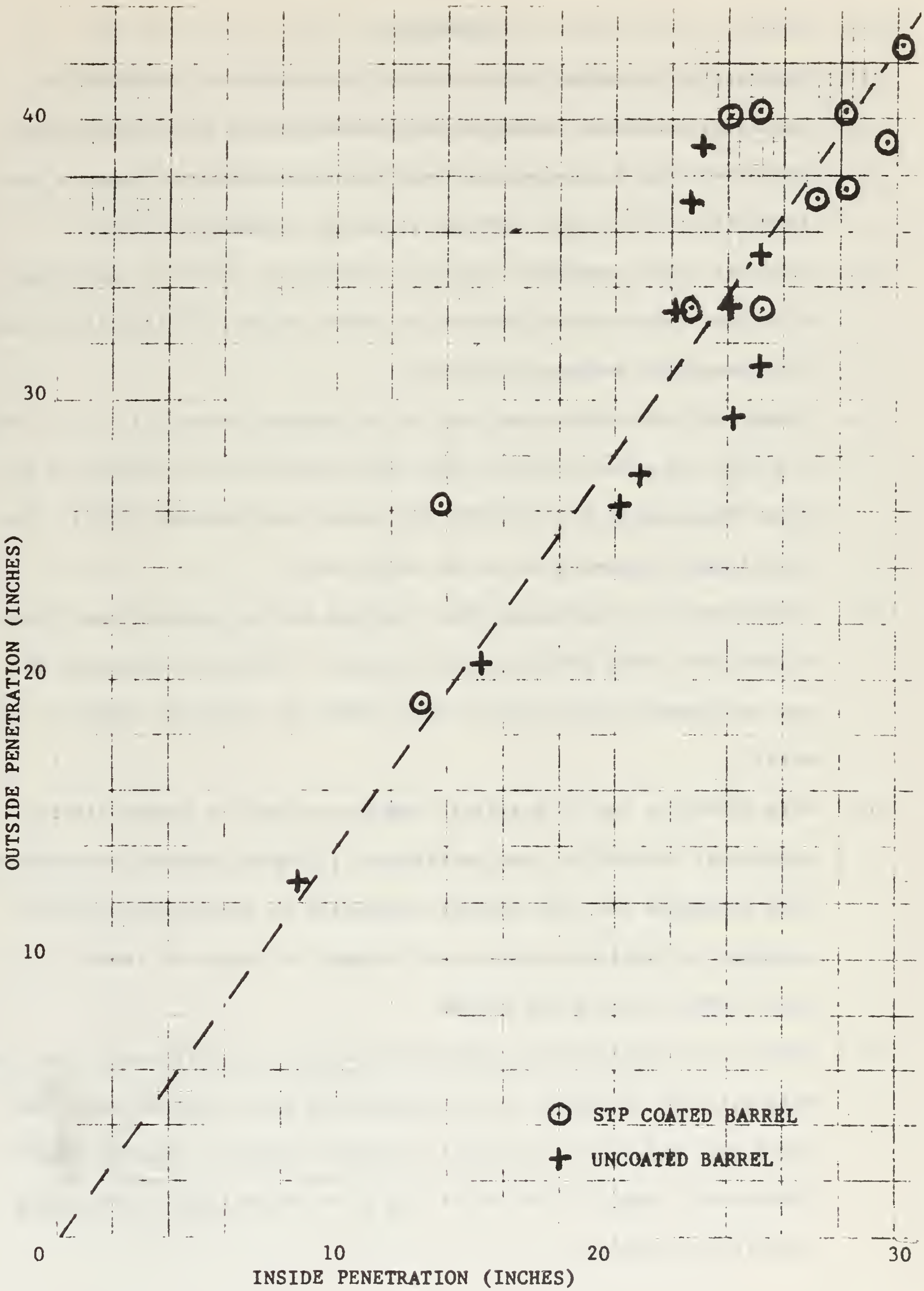

Figure 7. Comparison Penetration Data from Sea Test II

FINDINGS

1. Penetration of smooth steel surfaces into cohesive sediments was increased and shear stress was decreased through use of lubricants.
2. The laboratory test apparatus used in the present study gave a good indication of the best coatings to use in sea tests.
3. The dual corer apparatus used for simultaneous drops at sea helped eliminate the error of comparative tests caused by ship drifting and the consequent sediment variation.
4. Though no core catcher was used on the gravity corers (I. D. 1.4 and 1.6 in), the gross recovery ratio was about 60 to 70 percent of the total penetration for both the lubricated and uncoated corers. The core lengths ranged from one to three feet.
5. Laboratory tests indicated that coatings put on adhesive tape (such as FEP film) were unsatisfactory because of eventual loosening in a wet environment and therefore they should be thermally bonded to the metal.
6. More effective use of available energy was made by coated plates, especially during the slow penetration following dynamic penetration. This indicates that the greatest advantage of lubricants might be realized if lubricated corers are allowed to remain at least a minute after hitting the bottom.
7. Since the laboratory tests demonstrated that the frictional force per unit area was decreased by lubricating the steel surface area, and since wall friction is the most important factor in causing sample disturbance, sample disturbance should be decreased by lubricating core liner surfaces.

8. The laboratory tests indicated that a penetration resistance index obtained by taking the tangent of the angle of inclination is very similar to one obtained by dividing the maximum penetration resistance force by penetration; this confirms a suggestion made by Hvorslev (1949).

CONCLUSIONS

Tests conducted in both the laboratory and at sea indicated that use of lubricants and polymer coatings increase the penetration of smooth steel surfaces into fine grained sediments. In the laboratory tests the lubricants STP, CRC, zinc grease, and lithium grease increased penetration 46, 25, 24, and 20 percent respectively. Teflon, FEP film and nylon increased penetration 20 to 30 percent in the laboratory and merit special consideration since these coatings would not contaminate the core sample. Tests at sea showed that use of STP lubricant increased corer penetration 18 and 35 percent and gross recovery length of cores 16 percent.

FUTURE RESEARCH

Teflon, FEP, and Nylon coatings should be retested with special consideration since these coatings would not contaminate the core sample. Sample disturbance should be observed in addition to penetration increases. Combinations of lubricants such as STP on Teflon S should be tested. Pull-out tests should be included in order to compare the forces required to extract coated and uncoated metal surfaces from cohesive sediments.

If a Penetration Resistance Index were determined on various deep ocean sediments, comparative values representative of the density, consistency, or strength of the sediments could be obtained. Comparison of a Penetration Resistance Index determined at sea with an Index of the same sediment determined in the laboratory might give an indication of the physical properties of deep sea sediments.

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APPENDIX I

The circuit diagram (Figure 8) illustrates the nature of the electrical measuring devices (load cell and 20 K ohm potentiometer) and the circuitry used in the laboratory test apparatus.

The load cell and 20 K ohm potentiometer were calibrated before incorporating them into the test apparatus by using a Digitec D. C. Voltmeter, Model 251, United Systems Corporation. The calibration curves are shown in Figure 9. Calibration tests were conducted using the variplotter and the graphic results were compared with the voltmeter reading each day prior to testing.

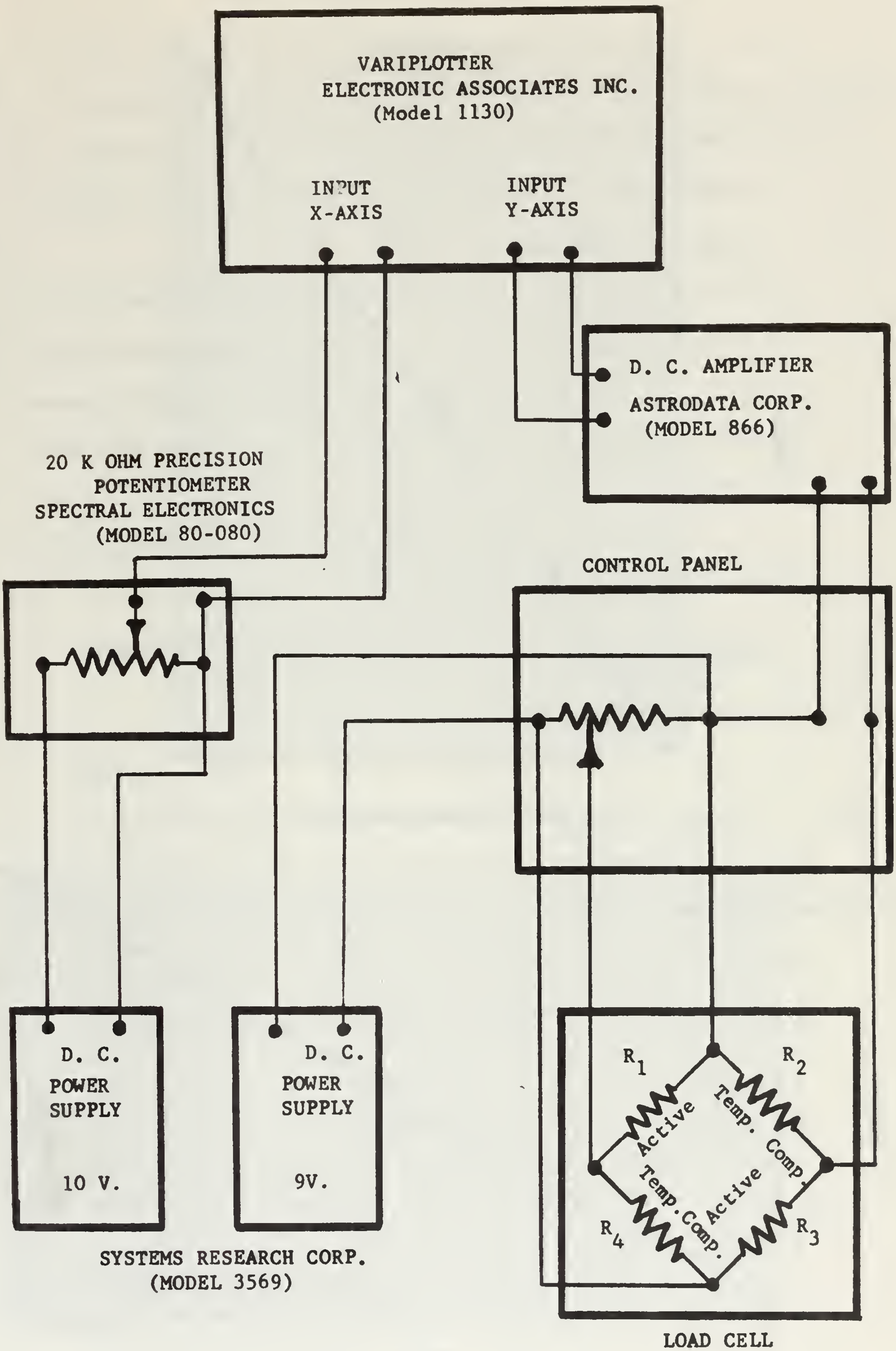
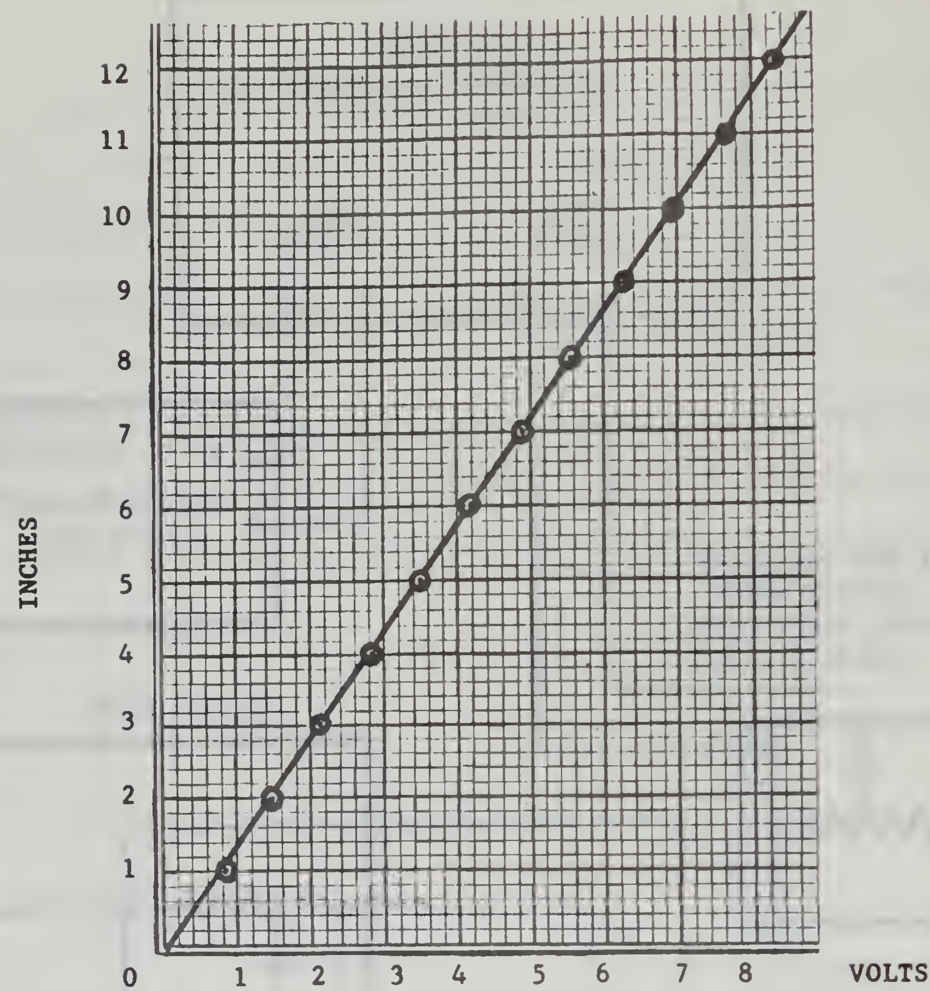


Figure 8. Circuit Diagram for Laboratory Test Apparatus

20K OHM POTENTIOMETER CALIBRATION CURVE



LOAD CELL CALIBRATION CURVE

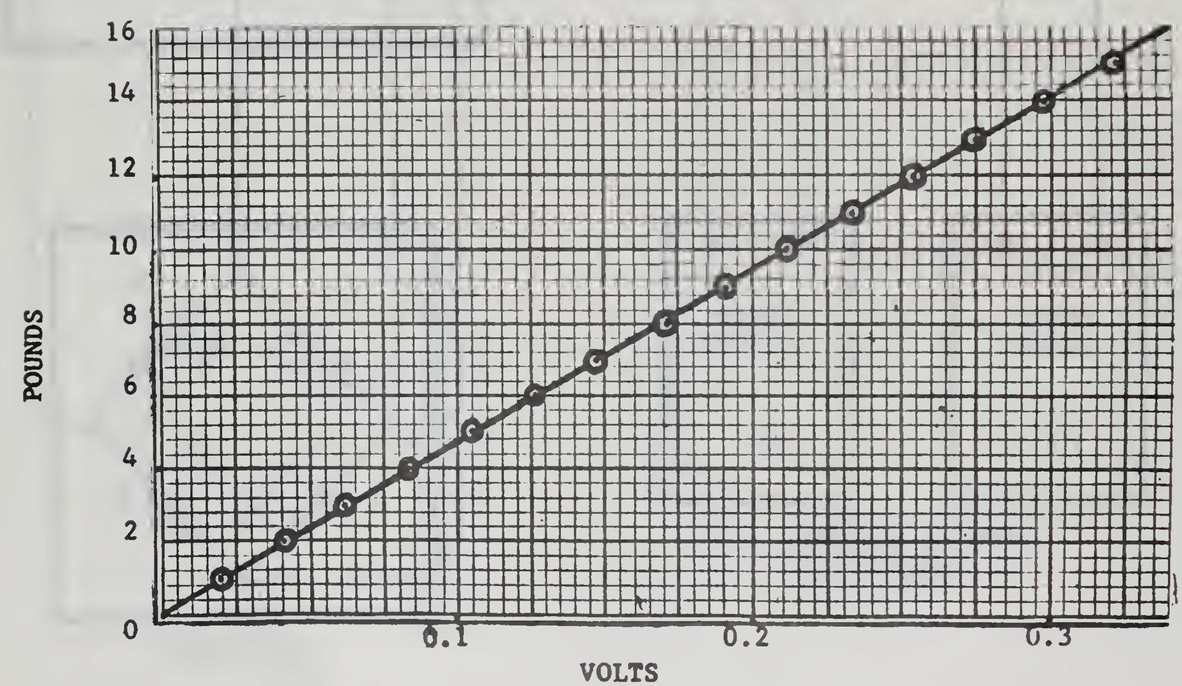


Figure 9: Load Cell and 20 K ohm potentiometer calibration curves.

APPENDIX II

A sample computation is presented below. The following information was read directly from the penetration resistance diagram (Figure 3) visually, by using a protractor, and by use of a planimeter:

	Control	Test
Dynamic Penetration (DP)	5.9 in	7.0 in
Total Penetration (TP)	6.5 in	10.3 in
Maximum Penetration Resistance (MPR)	9.2 lb	8.4 lb
Total Work (TW)	29.8 in-lb	47.4 in-lb
Angle of Inclination	39°	32°

Plate dimension 3 x 12 x 1/8 in

The following computations were made using the above information:

$$\text{Dynamic Penetration Increase (DPI)} = \frac{DP_{test} - DP_{control}}{DP_{control}} \cdot 100,$$

where DP is the dynamic penetration

DPI = 19%

$$\text{Total Penetration Increase (TPI)} = \frac{TP_{test} - TP_{control}}{TP_{control}} \cdot 100,$$

where TP is the total penetration.

TPI = 68%

$$\text{Computed Penetration Resistance Index} = \frac{MPR}{DP}$$

Computed PRI of control = 1.56

Computed PRI of test = 1.20

Measured PRI tangent of the angle of inclination = 1.62 (control)
(multiplied by two since the Y axis unit scale was ½ that of the X axis). 1.24 (test)

$$\text{Average Penetration Resistance Force (APRF)} = \frac{TW}{TP}$$

APRF of control = 4.6 lb

APRF of test = 4.6 lb

$$\text{Maximum Shear Stress} = \frac{\text{MPR}}{\text{Dynamic plate penetration area (in}^2\text{)}}$$

Maximum Shear Stress of control = 0.25 psi

Maximum Shear Stress of test = 0.19 psi

$$\text{Average Shear Stress} = \frac{\text{APRF}}{\text{Total plate penetration area (in}^2\text{)}}$$

Average Shear Stress of control = 0.11 psi

Average Shear Stress of test = 0.068 psi

$$\text{Decrease in Average Shear Stress} = \frac{\text{Av. SS}_{\text{control}} - \text{Av. SS}_{\text{test}}}{\text{Av. SS}_{\text{control}}} \cdot 100,$$

where SS is the shear stress.

Decrease in Average Shear Stress = 40%.

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13. ABSTRACT

The friction developed on the inner and outer faces of oceanographic coring tubes tends to decrease penetration and gross recovered length and to increase sample disturbance. An effort was made to decrease this friction through use of lubricants and polymer coatings and to thereby increase the penetration of smooth steel surfaces into fine grained sediments. Tests were conducted in the laboratory using steel plates and an Atwood test apparatus, and at sea using gravity corers. In the laboratory tests the lubricants STP, CRC, zinc grease, and lithium grease increased penetration 46, 25, 24, and 20 percent respectively. Tests at sea showed that use of STP lubricant increased corer penetration 18 and 35 percent and gross recovery length of cores 16 percent. Statistical analysis indicated that the above increases were highly significant. Teflon, FEP film, and nylon increased penetration 20 to 30 percent in the laboratory and merit special consideration since these coatings would not contaminate the core sample.

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